ASME STANDARDS TECHNOLOGY, LLC

STP-PT-080

DEVELOPMENT OF AVERAGE ISOCHRONOUS STRESS-STRAIN CURVES AND EQUATIONS AND EXTERNAL PRESSURE CHARTS AND EQUATIONS FOR 9CR-1MO-V STEEL

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FOREWORD

The purpose of this project is to develop isochronous stress-strain curves and external pressure charts in the creep regime for 9Cr-1Mo-V steel taking into consideration updated information and data available in the literature. The temperature range is 800ºF to 1200ºF. The time range is Hot Tensile up to 300,000 hours. The project is divided into four parts in order to accomplish the required tasks.

PART 1. In this part creep model equations are generated for 9Cr-1Mo-V steel. The equations and applicable current data are gathered from many sources as detailed and explained in this part.

PART 2. The physical data of Part 1 are converted in this part to equation form and combined with the stress-strain creep model equations in order to have a unified system usable for generating isochronous curves. Examples are given to demonstrate the feasibility of generating isochronous curves directly from equations for any temperature and time within the scope of this project. Isochronous stress-strain charts are also drawn for reference purposes.

PART 3. In this part equations are developed for the purpose of constructing external pressure curves and charts for the 9Cr-1Mo-V steel. These curves and charts, which are constructed from equations for various temperatures and times, are verified for accuracy against charts drawn directly from the isochronous curves by the graphical and finite difference methods.

PART 4. The equations derived in this part for designing components in the creep regime are applicable to all materials. They are included in this report to show the integration of design equations with equations used to construct external pressure curves in the creep range.

Reference is made throughout this document to the ASME BPVC Section III-NH Code. Presently all of the current contents in III-NH are also in Section III, Division 5 of the ASME BPV Code for nuclear class NB applications. However, it should be noted that Section III-NH is slated for elimination in the middle of 2017. At that time the material tables and charts in III-NH will be transferred to the ASME BPV Code Section II-D. Similarly, a revised text of the rules in III-NH will appear in ASME Code Case 2843 for Section VIII applications.

The authors extend their thanks to various members of ASME BPV I, II, III, and VIII Committees for their support of this project. It is hoped that the results generated in this report will benefit all of these codes. Special thanks are given to Dr. Kevin Jawad for obtaining the derivatives of some of the complicated equations in PART 3 of the report. Thanks are also given to reviewers Dr. Peter Carter, Mr. Don Kurle, Mr. Benjamin Hantz, Dr. John Grubb, and Mr. Robert Mikitka for their thoughtful comments and to Ms. Colleen O'Brien and Mr. Steve Rossi of ASME for coordinating various phases of this project.

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SUMMARY

The following tasks are accomplished for this project.

1. Isochronous stress-strain equations are developed for 9Cr-1Mo-V steel that take into account the elastic, plastic, and creep strain - prepared by Robert W. Swindeman and Michael J. Swindeman, Ph.D.

2. Isochronous stress-strain charts are developed from equations for 9Cr-1Mo-V steel. The temperature coverage is 800ºF to 1200ºF in increments of 50ºF. Curves in the charts cover time increments of Hot Tensile, 1 hour, 10 hours, 100 hours, 1000 hours, 10,000 hours, 100,000 hours, and 300,000 hours. In addition, equations are given to assist in plotting individual curves at any temperature and time within the scope of this project – prepared by Maan H. Jawad, Ph.D., P.E.

3. External pressure charts are generated from isochronous stress-strain equations for 9Cr-1Mo-V steel. The temperature coverage is 800ºF to 1200ºF in increments of 100ºF. Curves in the charts cover time increments of Hot Tensile, 10 hours, 100 hours, 1000 hours, 10,000 hours, 100,000 hours, and 300,000 hours. In addition, equations are given to assist in plotting individual external pressure curves at any temperature and time within the scope of this project – prepared by Maan H. Jawad, Ph.D., P.E. and Donald Griffin, Ph.D.

4. Equations are developed for designing components in the creep range under compressive stress for all materials. The equations cover axial compression in cylinders, external pressure in spherical components, external pressure in cylindrical shells, and axial compression in structural columns (Euler's buckling) – prepared by Maan H. Jawad, Ph.D., P.E. and Donald Griffin, Ph.D.

ABBREVIATIONS AND ACRONYMS (PART 1)

A = Parameter in the Ellis form of the creep equation, essentially the Monkman-Grant strain (mm/mm)
a_0, a_1, a_2, a_3 = Coefficients used in a Larson-Miller parametric expression
α = Creep rate acceleration term used in fitting the tertiary portion of the curve in the Ellis Model
α_1 = Creep rate deceleration term used in fitting the primary creep portion of the curve
α_3 = Creep rate acceleration term used in fitting the tertiary portion of the curve
B = Parameter in the Ellis form of the Creep Equation (1/hour)
(1/b) = a factor in the Voce equation adjusted to force the yield curve to pass through the Y-1, S_{y1}, or S_{ys} (%)
C = term in the Larson-Miller parametric expression, corresponding to the Larson-Miller Constant
Δ = an increment of stress that represents the difference between the minimum and average plastic flow curves and is equal to 0.25 Y-1 or 0.25 S_{y1}
e_p = plastic strain (%)
ε = Creep strain for any stage of the creep curve
ε_1 = Primary component of creep strain in a linear combined model
ε_3 = Tertiary component of creep strain in a linear combined model
ε_c = Combined primary and tertiary creep
ε_r = Total creep strain at rupture
$\dot{\varepsilon}$ = Creep strain rate (1/hour)
$\dot{\varepsilon}_0$ = Initial creep rate based on a fit to the tertiary stage of the creep curve in the Ellis Model (1/hour)
$\dot{\varepsilon}_{03}$ = Initial creep rate based on a fit to the tertiary stage of the creep curve (1/hour)
$\dot{\varepsilon}_1$ = Creep rate (1/hour)
$\dot{\varepsilon}_{01}$ = Initial creep rate based on a fit to the primary stage of the creep curve
F = Parameter used in the Ellis Model, the integration constant, which is related to the total Initial creep strain at time t = 0
K = Coefficient in the Andrade form for primary creep ($1/hr^{p+1}$)
p = Time exponent in the Andrade form for primary creep, normally 1/3
S_{pl} = proportional limit of tensile curve: minimum, average, or typical curve of concern (ksi)
S_u = stress value from Table NH-3225-1 in Section III Subsection NH which covers temperatures above 1000°F(ksi)
S_{uts} = ultimate tensile strength of the "average" curve (ksi)
S_{ys} = 0.2% offset yield strength of the "average" curve (ksi)
S_{y1} = Stress value from Table I-14.5 in Section III Subsection NH which covers temperatures Above 1000°F (ksi)
σ = Applied Stress (MPa)
t = Time at a specified stress (hours)
$t_{\varepsilon r}$ = Time to reach rupture strain (hours)
t_r = Rupture time (hours)
$(t_r)_3$ = Rupture time based on a fit to the tertiary portion of the curve (hours)
T = Temperature (°C)
U = stress value from Table U in ASME BPVC Section II Part D which covers temperatures to 1000°F (ksi)
Y-1 = stress value from Table Y-1 in ASME BPVC Section II Part D which covers temperatures to 1000°F (ksi)

1 GENERATION OF CREEP MODELS FOR 9CR-1MO-V STEEL (GRADE 91) ISOCHRONOUS CURVES

1.1 Introduction

The intent of this report is to describe the development of a creep model for use in producing isochronous curves for grade 91. The basis for the other component of strain, the plasticity or "hot tensile" curve, has been described elsewhere. Values of creep strain are needed over a wide range of conditions. At some temperatures, stresses, and times, the creep strain is dominated by the primary component; at other conditions tertiary creep is important. The model must in some cases be predictive of conditions for which there are no available data, specifically estimating creep strains at very low stresses, high temperatures, and long times.

In describing the model, we try to maintain a distinction between terms such as condition, parameter, constant, and coefficient. The conditions are the inputs to the model: stress, temperature, and time. The parameters of the model are the values that are used to describe the shape of the creep curve at a specific set of conditions. For example, the stress exponent, *n*, is a parameter, and the time to rupture, t_r, may also be considered a parameter. The model coefficients are used in describing the parameters as functions of stress and temperature. The term constant is only used for specific coefficients that take on a special role in a time-temperature parameterization. In this report, the term constant is exclusively used for the Larson-Miller constant. It is highly desirable to keep the number of parameters low to minimize the effort of determining the coefficients.

Many have come to view the classic three stage description of creep as the result of a primary stage where hardening mechanisms result in diminishing creep rates and a tertiary creep stage where damage and aging mechanisms produce an increasing creep rate. The second stage, where creep rate appears to be constant, is simply the transition between the two stages. Primary-tertiary forms for creep models often involve four parameters, two each for the primary and tertiary stages.

To determine these parameters, three approaches are possible. The first is to fit the entire curve. This can be quite difficult depending on the creep model since it involves non-linear regression. The second is to fit either the tertiary creep or primary creep and then make adjustments for the missing component. The third is to fit each separately and look for a method to combine the curves. The model proposed below seeks to use information contained within the tertiary creep portion of the curve to provide an estimate of the primary creep strain.

1.2 Logarithmic Creep Rate Formulation

<u>Description of Tertiary Creep</u>

The model expression for tertiary creep is[1]

$$\ln(\dot{\varepsilon}) = \ln(\dot{\varepsilon}_{03}) + \alpha_3 \varepsilon \tag{1.1}$$

where ε is the creep strain, $\dot{\varepsilon}$ is the creep strain rate, $\dot{\varepsilon}_{03}$ represents the initial creep rate at zero strain and α_3 provides the dependence of the strain rate on the creep strain. In the present paper, we refer to this form of the creep law as the logarithmic-rate form.

[1] The use of the term α is intentional and is used to distinguish the resultant values in the present approach from those values tabulated for aged material in ASME FFS-1 / API-579.